Microbial Risk Analysis 000 (2015) 1–7

Contents lists available at ScienceDirect

Microbial Risk Analysis

journal homepage: www.elsevier.com/locate/mran

Review of pathogen treatment reductions for onsite non-potable reuse of alternative source waters

Mary E. Schoen[a,*], Jay Garland[b]

[a] Soller Environmental, Inc., 3022 King St, Berkeley, CA 94703, United States
[b] National Exposure Research Laboratory, U.S. Environmental Protection Agency, 26 West Martin Luther King Drive, Cincinnati, Ohio 45268

ARTICLE INFO

Article history:
Received 29 July 2015
Revised 23 September 2015
Accepted 10 October 2015
Available online xxx

Keywords:
Risk assessment
Pathogens
QMRA
Non-potable
Reuse
Onsite
Graywater
Greywater
Blackwater
Wastewater
Rainwater
Stormwater
Treatment reductions

ABSTRACT

Communities face a challenge when implementing onsite reuse of collected waters for non-potable purposes given the lack of national microbial standards. Quantitative Microbial Risk Assessment (QMRA) can be used to predict the pathogen risks associated with the non-potable reuse of onsite-collected waters; the present work reviewed the relevant QMRA literature to prioritize knowledge gaps and identify health-protective pathogen treatment reduction targets. The review indicated that ingestion of untreated, onsite-collected graywater, rainwater, seepage water and stormwater from a variety of exposure routes resulted in gastrointestinal infection risks greater than the traditional acceptable level of risk. We found no QMRAs that estimated the pathogen risks associated with onsite, non-potable reuse of blackwater. Pathogen treatment reduction targets for non-potable, onsite reuse that included a suite of reference pathogens (i.e., including relevant bacterial, protozoan, and viral hazards) were limited to graywater (for a limited set of domestic uses) and stormwater (for domestic and municipal uses). These treatment reductions corresponded with the health benchmark of a probability of infection or illness of 10^{-3} per person per year or less. The pathogen treatment reduction targets varied depending on the target health benchmark, reference pathogen, source water, and water reuse application. Overall, there remains a need for pathogen reduction targets that are health-protective for non-potable reuse of onsite-collected waters. Also, future QMRA efforts should evaluate the importance of factors that are often overlooked such as the collection scale, sporadic pathogen occurrence, and possibly exposures resulting from misuse or failure events.

Introduction

Decentralized approaches to the reuse of alternative waters for non-potable purposes are of increasing interest in water-stressed regions to reduce pressure on drinking water supplies, as exemplified by the city of San Francisco's active program in non-potable water reuse (San Francisco Public Utilities Commision 2015). The onsite reuse of alternative water involves the collection, treatment, redistribution and reuse of water at different scales from an individual building to a district. For domestic and municipal purposes, potential sources of water for onsite treatment and reuse include:

- *Graywater*: wastewater from bathtubs, showers, bathroom sinks, and clothes washing machines, excluding toilet and—in most cases—dishwasher and kitchen sink wastewaters;
- *Blackwater*: wastewater from toilets and sometimes including kitchen sink wastes;
- *Rainwater*: precipitation collected from roof surfaces or other above ground collection surfaces;
- *Stormwater*: precipitation collected from the ground level; and
- *Seepage water:* precipitation that has passed through soil.

These waters contain both chemical and microbial contaminants that can result in a range of human health outcomes when ingested, inhaled, or absorbed through the skin (Chapman et al. 2008; Deere et al. 2006; McBride et al. 2013). Communities face a challenge when implementing onsite reuse for non-potable purposes given the lack of national microbial standards. NSF/ANSI Standard 350 for non-potable onsite reuse of graywater recommends the monitoring of fecal indicators to test for acceptable finished water quality (NSF International 2015). However, the lack of a relationship between fecal indicators and human-infectious pathogens in graywaters, as well as rainwaters, remains a major problem when relying on fecal indicators to indicate finished water quality and potential human health risk (Ahmed et al. 2011; Ahmed et al. 2010a; O'Toole et al. 2012).

Quantitative Microbial Risk Assessment (QMRA) is a scientific approach that calculates the potential human health risk resulting from exposure to microbial hazards (e.g., human pathogenic viruses,

* Corresponding author. Tel.: +1 330 705 2011.
E-mail addresses: mschoen@sollerenvironmental.com (M.E. Schoen), Garland.Jay@epa.gov (J. Garland).

http://dx.doi.org/10.1016/j.mran.2015.10.001
2352-3522/

protozoa, and bacteria) (Haas et al. 1999). A limited number of QMRAs predicted the potential health risk associated with onsite reuse applications (see the literature review summary in the Results for a full list of studies). These QMRAs followed the traditional steps in a forward process: problem formation, exposure assessment, dose-response assessment, and risk characterization (Haas et al. 1999). In a forward QMRA process, reference hazards are selected for the exposure scenario of interest in the problem formation step; reference hazards represent classes of pathogens with potential adverse health impacts. For the waters listed above, the reference hazards include enteric pathogens resulting from human or animal fecal contamination as well as opportunistic pathogens (e.g., *Legionella pneumophila*) which may grow within the collection and distribution systems (Chapman et al. 2008; O'Toole et al. 2014). In the exposure assessment, the dose of each reference hazard is estimated while accounting for exposures from all intended uses (e.g., for domestic use this may include household and garden exposures) and, for some QMRAs, accidental exposures. Following, the dose is used in a peer reviewed dose-response relationship to estimate the probability of infection (or illness) per person exposed. In the final risk characterization, the resulting predicted risk is compared to a health benchmark either reported as a probability of infection (or illness) or converted to Disability Adjusted Life Years (DALYs) (i.e., the sum of years of life lost by premature mortality and years lived with disability (Murray and Acharya 1997)).

QMRA can also be conducted in the reverse order, starting with a health target, to predict either the tolerable pathogen densities or pathogen treatment requirements. Using the reverse approach, the World Health Organization (WHO) and Australian government published guidelines for pathogen $\log_{10}$ treatment reductions of fecal pathogens (e.g., human pathogenic viruses, protozoa, and bacteria) for a limited number of reuse applications (see Supporting information for more details on the reverse approach used by WHO and others) (NRMMC et al., 2006, 2008, 2009; World Health Organization, 2006b). In the mentioned guidelines, the treatment reductions corresponded to the health benchmark of 10^{-6} DALYs per person per year (ppy). This benchmark is consistent with the WHO Guidelines for Drinking-Water Quality (World Health Organization, 2011) and is approximately equivalent to an annual diarrheal risk of infection of approximately 10^{-3} ppy for *Rotavirus* or *Cryptosporidium* and 10^{-4} ppy for *Campylobacter*.

To identify health-protective pathogen treatment requirements for onsite non-potable reuse, we reviewed the QMRA literature and summarized the human health risks associated with the reuse of onsite-collected waters as well as pathogen treatment reduction targets. We reviewed both the forward and reverse QMRA literature in order to:

1. Identify onsite non-potable reuse scenarios with little or no previous risk assessment;
2. Identify onsite non-potable reuse scenarios that may require pathogen treatment;
3. Summarize reported treatment reductions that correspond with the WHO target health benchmark; and
4. Identify factors that are important for the calculation of pathogen $\log_{10}$ treatment reductions for onsite reuse systems, including gaps in our current understanding.

Methods

We conducted a literature review of QMRA publications to identify assessments of onsite domestic, commercial, and municipal reuse of alternative waters. Databases included Biological Abstracts, Environmental Databases, PubMed, Sci Search, Current Contents, and Waternet. Search terms included (("quantitative microbial risk assessment" OR (QMRA and "risk assessment")) AND (reuse OR re-use OR recycl*) AND ("non-potable water" OR Rainwater* OR stormwater* OR graywater OR graywater* OR wastewater* OR "waste water" OR blackwater*)). The findings from the literature review were converted to median or mean annual probability of infection or illness using the assumptions and calculations from each individual publication. Generally, risk was reported for the individual and not over the population at large. When risk was reported over the population (e.g., annual infection risk per 10,000 people in Ahmed et al. (2010b)), we used the risk divided by the population to avoid reproducing individual risk estimates. In this case, the risk to specific individuals may be higher than the average risk over the population. For studies that reported results for numerous sites or scenarios for the same exposure scenario, we report the highest and lowest predicted risk.

Results

Summary of non-potable reuse publications

The literature search returned 46 publications. Forward QMRA studies with a focus on centralized systems and industrial or agricultural applications were not reviewed. QMRA studies with unreported pathogen removal were not reviewed. Of those remaining, non-potable reuse was modeled in 1 study of wastewater/blackwater (NRMMC et al., 2006), 5 of graywater (Barker et al., 2013a; Deere et al., 2006; Ottoson and Stenström, 2003; Schoen et al., 2014; World Health Organization, 2006b), 5 of stormwater (de Man et al., 2014b; Lim et al., 2015; NRMMC et al., 2009; Page et al., 2012; Sales-Ortells and Medema, 2014), 7 of rainwater (Ahmed et al., 2010b; de Man et al., 2014a; Fewtrell and Kay, 2007; Lim and Jiang, 2013; NRMMC et al., 2009; Oesterholt et al., 2007; Schoen et al., 2014), and 1 of seepage water (Oesterholt et al., 2007). Of the studies on non-potable reuse of blackwater and graywater, onsite applications were specifically addressed or discussed in 0 studies of blackwater and 4 of graywater (Barker et al., 2013a; Deere et al., 2006; Ottoson and Stenström, 2003; Schoen et al., 2014). Page et al. (2012) was not included in the review because it discussed the NRMMC et al. (2009) stormwater QMRA work, but did not present new risk estimates.

Onsite non-potable reuse scenarios ranked by risk

The results of the QMRA literature review are presented for graywater (Fig. 1 and Supporting information Table 1), stormwater (Fig. 2 and Supporting information Table 2), rainwater (Fig. 3 and Supporting information Table 3), and seepage water (Fig. 4 and Supporting information Table 4). In Figs. 1–4, the median or mean $\log_{10}$ pathogen reductions are plotted against the corresponding mean or median annual probability of infection (or illness), as reported in the original studies, for each reference hazard. Multiple predicted risks are presented for reuse scenarios that have more than one risk assessment (e.g., rainwater reuse for toilet flushing). The mid-range value (i.e., mean or median, as reported) of the $\log_{10}$ pathogen reductions is plotted when variable treatment performance was assumed (e.g., graywater reuse for irrigation or stormwater reuse for showering), or, in the case of reverse QMRA, when variability in the pathogen dose was estimated (e.g., graywater reuse for toilet and garden use).

The scenarios with at least one reference pathogen with a reported annual probability of infection greater than 10^{-3} ppy; between 10^{-4} and 10^{-3} ppy; or less than 10^{-4} ppy are listed below. The reference pathogen with the highest probability of infection (or highest required log reduction) for the exposure scenario is listed in parenthesis. When different levels of treatment were applied to the reference pathogens in the same exposure scenario, the pathogen with the highest risk could not be determined in some cases.

Scenarios with annual probabilities of infection greater than 10^{-3} ppy, and ordered with the highest risk first, included: